PERMAFROST HYDROLOGY: THE ALASKAN EXPERIENCE

BY

ROBERT F. CARLSON

Workshop Seminar on Permafrost,
CNC/IHD Calgary, Alberta
Feb. 26-28, 1974

Surface Waters Session

PERMAFROST HYDROLOGY: THE ALASKAN EXPERIENCE

Robert F. Carlson

Abstract

Most permafrost in Alaska is found north of the Alaska Range. The region between the Alaska Range and the Brooks Range is considered to be discontinuous and the area north of the Brooks Range continuous.

Surface water studies usually deal with flood design as it relates to stream crossings and valley occupation, water supply, stream use as a means of conveyance, and basic process studies. This paper examines the state of knowledge of surface water in Alaska as it is primarily affected by permafrost, and also points out the correlation of effects due to high latitude, cold temperatures, elevation differences, and extreme lack of background data.

The greatest effort in surface water hydrology in Alaska has dealt with flood and basic process studies. Research along with the normal data gathering efforts has been carried out in the North Slope region by federal agencies, large integrated research studies, and smaller individual research projects, all largely in response to the development activity initiated by the Alaska pipeline.

The approach taken by the Institute of Water Resources (IWR) of the University of Alaska has been devoted to conceptual model studies of floods and process dynamics. The primary intent of the models is to concentrate on a few meaningful parameters that adequately describe the data. The model efforts have been applied in several instances, most extensively in a North Slope project that has two parts, a snowmelt model and a basin model. The adequacy of the approach, especially with the available data, is discussed. The IWR model in turn has been used by Dingman for the International Biological Programme. A further attempt has been made to understand the dynamics of flood frequency of snowmelt storms with the most intensive application being made to the Chena River Basin near Fairbanks.

Another problem peculiar to the permafrost regions is the occurrence of aufeis. Although it would seem that aufeis is a surface phenomena, the discussion will show it to be largely a groundwater phenomenum and therefore, it will not be extensively discussed in this paper. The groundwater hydraulics aspect of aufeis occurrence and of research in progress are briefly discussed.

The combined factors of scarcity of data, high latitude, and cold temperatures, which cloud the role of permafrost in hydrology, lead to the conclusion that a need exists for a special viewpoint of hydrologic analysis in the Arctic. This viewpoint should include an intensive use of mathematical modelling techniques, a strong reliance on physical process description, and techniques which make full use of the available sparse data.

Résumé

En Alaska, le pergélisol se trouve pour la plupart au nord de la chaîne de l'Alaska. La zone qui sépare cette dernière de la chaîne Brooks est discontinue, tandis que la région située au nord de la chaîne Brooks est continue.

L'étude des eaux superficielles porte d'habitude sur la conception des flots appliquée aux croisements des cours d'eau et à l'occupation de vallées, à l'approvisionnement en eau, à l'utilisation des cours d'eau pour le transport et aux processus de base. Dans le présent document, on examine l'état des connaissances sur les eaux superficielles de l'Alaska, étant donné qu'elles sont principalement touchées par le pergélisol, et souligne également la corrélation entre les effets causés par les hautes altitudes, les basses températures, les différences d'altitude et le manque extrême de données de base.

Le plus grand effort concernant l'hydrologie des eaux superficielles de l'Alaska a porté sur l'étude des flots et des processus de base. La recherche ainsi que les efforts normaux pour récolter des données ont été effectués dans la zone du versant Nord par les organismes fédéraux, d'importants groupes d'études et des chercheurs indviduels, dans le cadre des travaux de construction du pipe-line de l'Alaska.

L'approche de l'Institute of Water Resources (IWR), qui relève de l'Université de l'Alaska, s'est concentrée sur l'étude conceptuelle sur l'étude conceptuelle de modèles de flots et de dynamique des processus. Le premier objet des modèles est de mettre l'accent sur quelques paramètres significatifs qui décrivent convenablement les données. La création de modèles a été appliquée dans plusieurs cas, particulièrement dans le programme du versant Nord qui comprend deux parties^ un modèle de fonte des neiges et un autre de bassin. On discute de l'opportunité de cette approche, spécialement avec les données disponibles. Le modèle de l'IWR a été également employé par Dingman dans le cadre du Programme biologique international. Par la suite, on a tenté de comprendre la dynamique de la fréquence des flots de tempêtes de neige fondue, l'application la plus intensive ayant été faite pour le bassin de la rivière Chena près de Fairbanks.

Un autre problème typique des régions de pergélisol est la formation de buttes en lentilles de glace. Bien que ce phénomène semble n'être que superficiel, on verra d'après les discussions que c'est en grande partie un phénomène propre aux eaux souterraines. Par conséquent, on n'abordera pas la question en profondeur dans la présente communication. On traite également de façon sommaire de l'aspect hydraulique des eaux souterraines dans la formation de lentilles de glace ainsi que de la recherche encours.

Les facteurs combinés du manque de données, des hautes latitudes et des basses températures, qui voilent le rôle du pergélisol en hydrologie, mènent à la conclusion qu'on a besoin d'un point de vue spécial quant à l'analyse hydrologique dans l'Arctique. Ce dernier devrait inclure l'emploi intensif des techniques mathématiques de création de modèles, une profonde confiance dans la description des processus physiques, ainsi que des techniques visant à utiliser au maximum le peu de données disponibles.

PERMAFROST HYDROLOGY - THE ALASKAN EXPERIENCE

INTRODUCTION

Early in 1968 the petroleum industry announced a major oil discovery on Alaska's North Slope. Plans for a large pipeline to the Gulf of Alaska promptly followed and in the years since, further plans have been made for another oil line and two gas lines. Most observers predict a great number of additional roads and feeder lines throughout Alaska's North in the near future.

This resource development activity is important to the subject of permafrost hydrology. An understanding of both permafrost and hydrology, separately and together, are absolutely vital for a speedy construction and uninterrupted operation of these transportation systems without undue disruption of environmental concerns.

This paper will discuss some key features of permafrost hydrology with particular reference to the development of transportation systems in the northern regions of the world and especially as it relates to the Alaskan experience.

PERMAFROST AND PERMAFROST REGIONS

Because of the experience and expertise in permafrost science represented here, it will not be necessary to discuss the nature of permafrost in detail. I will only examine the role of permafrost as a geologic agent in altering the hydrologic system of northern regions and present some collaborative effects present in cold regions.

The extent of permafrost in Alaska is shown in Figure 1. The permafrost in the region north of the Brooks Range is considered to be entirely continuous with thicknesses estimated up to 2,000 feet. Progressing from the Brooks Range southward to the Alaska Range, the permafrost becomes less and less continuous. The Fairbanks area permafrost is very warm and sporadic. Continuing southward, permafrost extends along the Copper River Valley, nearly reaching the Gulf of Alaska coast. Permafrost exists, of course, throughout the great river valleys of the Yukon and the Kuskokwim.

Although a seemingly simple and straightforward subject, permafrost hydrology presents a great number of difficulties in assessing the role of permafrost in the hydrologic system. Its most well known role is that of a geologic condition which presents a relatively impermeable barrier near the ground surface. The barrier, of course, is very temperature-dependent and complex, especially in regions of sporadic permafrost where a great number of perforations exist under the larger lakes and streams. The presence of unfrozen water also occurs within the frozen zone.

Characterization of permafrost hydrology is made more difficult by the existence of other agents in collaboration with permafrost, each of which offers a certain set of complexities. These are low temperature, high latitude, large elevation differences and an extremely sparse data network. Discussion of permafrost hydrology must address the roles of all five, these four and permafrost itself, in modifying the hydrologic system as it is normally found in northern regions. Each adds to the difficulty of studying permafrost hydrology and each should be addressed through a theory or model of understanding, with full realization of the amount of data available to confirm the theory or model, and with a certain problem in mind.

HYDROLOGIC SYSTEM CHARACTERISTICS, MODELS, AND PROBLEMS

The characteristics and linkage mechanisms of the various components of the total hydrologic system must first be considered when discussing permafrost hydrology. In a general way, this can best be expressed by the diagram shown in Figure 2 which has been adapted from Dooge (1967). This representation of the hydrologic system includes components for the atmosphere, surface storage, soil-water, groundwater, and a channel network, including channels, rivers and lakes. The ocean is the final reservoir of this hydrologic system. The representation is primarily one of mass flow, however, energy and momentum conservation also play an important part. Each of the components relates to, or is affected by, the five conditions of permafrost in a special way.

Models of understanding must be constructed to analyze permafrost hydrology processes. There is no good reason why models are not important. We must have them. If not, we have no basis for relating data-gathering and engineering problems.

There are many criteria for a great variety of models and model-building. It would seem, however, that we particularly need models for cold regions which have a basis closely related to

Although a knowledge [illegible] groundwater hydrology provides a great number of [illegible] of the hydrologic cycle. Its most well-known [illegible] a relatively impermeable borehole [illegible] the ground surface. The [illegible] place, especially [illegible] [illegible]

[illegible]

[illegible]

The characteristics [illegible]

[illegible] components related to, [illegible]

Models of understanding [illegible] There is no good reason why models are not [illegible] basis for relating data-gathering and engineering analysis.

There are many criteria for a good [illegible] of models and understanding. It [illegible], however, that we particularly need models for [illegible]

sound physical fundamentals and which are simple because of the extreme lack of verifying data. If a lack of knowledge forces a descriptive view, the descriptive view should be quantitative to provide the most useful transfer of information.

In addition to the consideration of the various components of the hydrologic system and the way in which they are affected by the conditions of permafrost regions, consideration must also be given the various kinds of problems which must be studied in connection with any hydrologic system. There are a number of different ways in which these may be expressed. Eagleson (1970) offers a particularly useful list of major categories of hydrologic problems:

(1) mean values: monthly, seasonal, annual, and other long-term averages of precipitation, streamflow, evaporation, groundwater level and others which are in themselves spatial averages covering large geographical areas

(2) extreme values: maximum and minimum values of precipitation and other hydrologic variables of interest which are the usual criteria for determining the size and specification of engineered structures in connection with water resource facilities

(3) time histories: complete time histories of the various responses of a hydrologic system to its particular excitations. These are particularly important in detailed design and operation of water resource facilities and in real time forecasting. These types of studies are also quite important to a detailed examination of the interreaction of the various components of the hydrologic system.

The primary job of the permafrost hydrologist, then, is to find the analytic relationship between inflow and outflow and the state of the system. However, often an adequate model cannot be constructed because of inadequate knowledge, unknown system heterogeneities, unknown time dependencies, and approximations which must be introduced for computational expediency.

THE COMPONENTS OF THE PERMAFROST HYDROLOGIC SYSTEM

Each of the hydrologic components are now examined from the point of view of its relationship to the five permafrost region characteristics.

Because of time and space limitations, complete reference to most of the hydrologic work which has been carried out in Alaska for the past several years will not attempted. Comprehensive reviews and bibliographies are available in Williams and Van Everdingen (1973), Dingman (1973), and Hartman and Carlson (1970).

The atmosphere component of permafrost hydrology systems is probably the least understood, yet offers a very important part in a complete understanding. No effect of permafrost upon the atmosphere exists. Low temperatures certainly have an effect, primarily through the division of atmospheric processes into rainfall and snowfall and through the consequent release of a large amount of surface water during the spring breakup season. High latitude has an effect in addition to its contribution to low temperatures in that a dramatic increase in solar radiation occurs during the springtime with a long sustained radiation throughout the northern summer. Elevation differences have a very profound effect on the atmospheric component, especially in Alaska where very steep gradients give rise to the condition of few major basins with less than several thousand feet of elevation difference. Sparse data is a particularly important condition in understanding the atmospheric component. Very few good precipitation and temperature gauges exist. Where they do, they are extremely stratified and measure conditions present in the lower elevations. Only crude estimates of other atmospheric conditions are available.

The surface storage system is, of course, of primary interest to resource development in permafrost regions and to permafrost hydrology. It is here that a great deal of the snowfall is stored until the spring breakup season and it is here also that a large amount of the mass and energy transfer takes place between this component and the atmospheric component. It is extremely difficult to understand this system both because of its great spatial and temporal variability and because of a great dependence upon the snow surface when it is present and the vegetative surface when the snow is not present. This component has a major relationship with the atmosphere, with the channel component and with the soil component. Again data is lacking; only a few snow courses exist in higher elevations.

The soil component is of primary interest to permafrost hydrologists because it is here that the permafrost and the coincident active layer exists. Low temperatures are also important due to the effect upon plants. High latitude and elevation differences are also important. Extremely little data is available for understanding the soil component, especially the complex relationship between mass and energy transfer in the unfrozen zone and the free water in the frozen zone.

The groundwater component of the hydrologic system plays an extremely important role in permafrost hydrology. The component has a major relationship with the soil component in areas

of sporadic permafrost and directly with the channel network in areas of more continuous permafrost. The groundwater component also has a major relationship through interactive flow with streams and lakes and is probably the primary mechanism for the occurrence and control of stream icings and aufeis deposits. The permafrost condition is a major contributing factor in understanding the groundwater component; low temperature, high latitude, elevation differences play a less direct role. Again, the extremely sparse data network affects most models and studies of the groundwater condition in permafrost regions.

The last component of interest to permafrost hydrologists is the channel network, including streams, rivers, lakes and other features that have major connections to some type of surface network. This component is probably of primary interest to permafrost investigators, practitioners, and scientists alike. In its role as the recipient of all the other processes, it demands complete understanding. Here also most engineering structures and problems in cold regions occur. The permafrost condition plays a very important role in understanding the channel network particulary in its role of forming a relatively impermeable boundary to streamwater flow. Low temperature plays an important role through its effect on conditioning the channel networks as having an ice, free water or an intermediate state. High latitude plays a dominant role as does elevation difference. High latitude affects the dramatic spring breakup condition. Elevation differences cause very steep gradients which offer a special type of stream condition. Sparse data network is extremely important here both in its direct influence on the design of engineering structures and also because measurements on channel network usually form what is often the only long-term reliable indication of the state of the whole hydrologic system.

The whole permafrost hydrology system is affected by all five of the permafrost conditions *i.e.* the permafrost condition itself, low temperature, high latitude, elevation differences and sparse data. Usually, the only available measurements of the system are relatively meager ones of atmospheric inputs, primarily temperature and precipitation, and of the output, usually streamflow. Intermediate components are generally neglected or unmeasured. For example, the transfer between the various components and the states of the system such as soil moisture, lake levels, groundwater levels, and permeabilities, are seldom directly studied or modeled.

MAJOR PROBLEMS OF PERMAFROST HYDROLOGY

Resource development in northern areas is occurring with startling rapidity. Problems will be many and varied. Of those in the areas of permafrost hydrology, several seem to dominate. There is a need for a better understanding of engineering intrusions on stream and river crossings. One class of problems would be directed toward occurrences of high flows and water levels, another toward river and river bottom mechanics. Another class of problems deals with the mass and energy transfer in natural and engineered permafrost soils. Time and space does not permit a complete discussion of all the problems associated with the expected resource development in northern regions. Other problems in hydrology will be those associated with water supply, waste disposal, and recreation.

THREE PROBLEMS IN ALASKA AND AN APPROACH TO THEIR SOLUTION

By way of illustration of the kinds of problems which can occur in permafrost hydrology and how an efficient approach to this solution might evolve, three examples will be discussed.

The first deals with flood design, an extreme-value problem. Selection of an appropriate design flood for a particular class of stream-crossing is one of the most challenging problems in any region, but particularly so in cold regions. The usual approach to the problem is through statistical models which, in turn, must be evaluated on the basis of past data, a difficult procedure when attempted in regions of little or no data. A regional regression approach may be tried but even this becomes difficult where, instead of several gauging stations or data points per homogeneous region, there are several homogeneous regions per gauge. One approach might be to choose appropriate frequency distributions of two of three parameters (certainly no more than three) and estimate the parameters by appropriate techniques on the basis of what streamflow information is available. The regional nature of the frequency parameters themselves might then be examined using the two or three parameters and some type of topographical or map correlation attempted.

Another difficulty with frequency analysis in northern regions other than that of little data is the reality of a rather complex hydrology in terms of its spring breakup, an event which often is not measured. In relatively settled areas, a great number of point estimates for measurements of rainfall and streamflow exist for a relatively long history. However, in

the case of a snow-dominated region where large amounts of spring runoff occur every year, an attempt must be made to assess the nature of the spring melt runoff.

The following approach has been used in a research program at the University of Alaska. The first step is to extract and estimate a reasonable model of the snowmelt runoff process. Application has been made to Alaska's North Slope region (Carlson, Norton, and McDougall, 1973) and to the Chena River (Carlson, 1974). A physically-based snowmelt model is applied to each of four elevation bands. Several test runs have indicated a reasonable fit to the measurements of snow courses during the melt season. The next step is to calculate the resulting snowmelt runoff and to treat it as if the occurrence had been one of measured precipitation and then to proceed with a frequency analysis in which the snowmelt runoff estimate is reduced to the frequency-depth-duration relationship. Then, following a method developed by Eagleson (1973), a runoff model is inserted to calculate the flood frequency relationship. The advantage of this method is that only two or three parameters of the runoff process need be estimated and they have a direct relationship to basin characteristics. Many approximations and estimates still exist, but this model has relatively few parameters, a critical criteria in cold regions with few years of hydrologic data.

A problem unique to cold regions, and a particularly perplexing one is that of stream aufeis or icing. This problem represents one of time history and may best be understood in a local rather than regional context. It is a hydraulic phenomenon which can be modeled with a fair degree of accuracy. The model should be rather straightforward and have a sound physical base.

A long-term, low-level research effort at the University of Alaska is studying the hydraulic mechanism of aufeis occurrence in a small subarctic stream (Kane, Carlson, Bowers, 1973). The study to date has indicated a great fluctuation of groundwater pore pressures and a resulting large interchange between the stream and the adjacent groundwater aquifer.

Another example of a problem of the time history type is soil water motion in the frozen soils. Guymon and Luthin studied the problem through a comprehensive computer model and field effort (Luthin and Guymon, 1973; Guymon and Luthin, 1974). The project results illustrate that a careful field program must be carried out throughout the entire hydrologic season when

attempting to understand a physical process in cold regions and that the physical representation of the process must be complete and thorough. In this case, it was found that the combined phenomena of mass and heat transfer is extremely important to an understanding of the total motion of soil water in frozen soils. The successful modeling of a one-dimensional mass and energy transfer should be useful in the design and understanding of engineered embankments and cuts for transportation systems in cold regions. Particularly interesting applications can be made in the construction of hot and cold pipelines.

SUMMARY

An attempt has been made to show the relationship of the various components of the permafrost regions: the permafrost condition itself, low temperatures, elevation differences, high latitude and sparsity of data. When attempting to construct a model or theory of understanding of permafrost hydrology processes, particular attention must be paid to these five conditions and to the particular kind of problem at hand, that is, whether it is a mean value, an extreme value or a time history problem. The models of understanding should have the characteristic of simplicity and yet be as faithful to the physical system as the problem will allow. In cases where a lack of understanding precludes construction of an adequate model, a descriptive approach must be quantitative to be useful and transferrable outside of the data area.

Because of the rapid development taking place in cold regions, particularly in the United States and Canada where there is a lack of knowledge of permafrost hydrology, there is a need for closely coordinated laboratory, field, modeling and design effort. Einstein (1972) has pointed out that there tends to be four classes of papers and investigators: theoretical, laboratory, field, and design and all tend to use different languages. Also, he states, with particular pertinence to permafrost hydrology:

> "It is most important, no matter what we are doing, to always remember that it is the design engineer who, in the end, will make use of what we have learned."

Without question, a need exists for more investigation of permafrost hydrology. However, in view of the relatively short time in which a great deal of knowledge must be gained with regard to the particularly critical problem at hand, it certainly behooves those of us who study hydrology of permafrost regions to make the utmost effort to advance a coordinated, well balanced program of studies. This workshop symposium is certainly a fine first effort.

REFERENCES

Carlson, R. F. (1974). Flood frequency design in regions of sparse data. Research in progress, OWRR Project B-030-ALAS. Institute of Water Resources, University of Alaska.

Carlson, R. F., W. Norton, and J. McDougall (1973). Modeling snowmelt runoff in an arctic coastal plain. Report No. IWR-43, Institute of Water Resources, University of Alaska.

Dingman, S. L. (1973). The water balance in arctic and subarctic regions. Special Report 187, U.S. Army - CRREL, Hanover, N. H. 134 pp, June.

Dooge, J. C. I. (1967). The hydrologic system as a closed system. Pro. International Hydrology Symposium, Colorado State University. Sept. pp 98-113.

Eagleson, P. S. (1972). Dynamics of flood frequency. *Water Resources Research*, 8(4). August, pp 978-898.

Eagleson, P. S. (1970). *Dynamic Hydrology*. McGraw-Hill.

Einstein, H. A. (1972). Remarks, Chap. 27 in Sedimentation Symposium to Honor Professor H. A. Einstein, H. W. Shen, Ed., Fort Collins, Colorado. pp 27-7 to 27-9.

Guymon, G. L., and J. N. Luthin (1974). A coupled heat and moisture transport model for arctic soils. Submitted to *Water Resources Research*.

Hartman, C., and R. F. Carlson (1970). Bibliography of arctic water resources. Report No. IWR-11. Institute of Water Resources, University of Alaska, College, Alaska. November.

Kane, D. L., R. F. Carlson, and C. E. Bowers (1973). Ground pore pressures adjacent to subarctic streams. No. American Contribution Permafrost, Second International Conference. Yakutsk, U.S.S.R., National Academy of Sciences, Washington, D.C.

Luthin, J. N. and G. L. Guymon (1973). Soil-moisture-vegetation-temperature relationships in Central Alaska. Submitted to [illegible].

Williams, J. R. and R. O. van Everdingen (1973). Groundwater investigations in permafrost regions of North America: a review, North American Contribution, Permafrost Second International Conference, Yakutsk, U.S.S.R. National Academy of Sciences, Washington, D.C. pp 435-446.

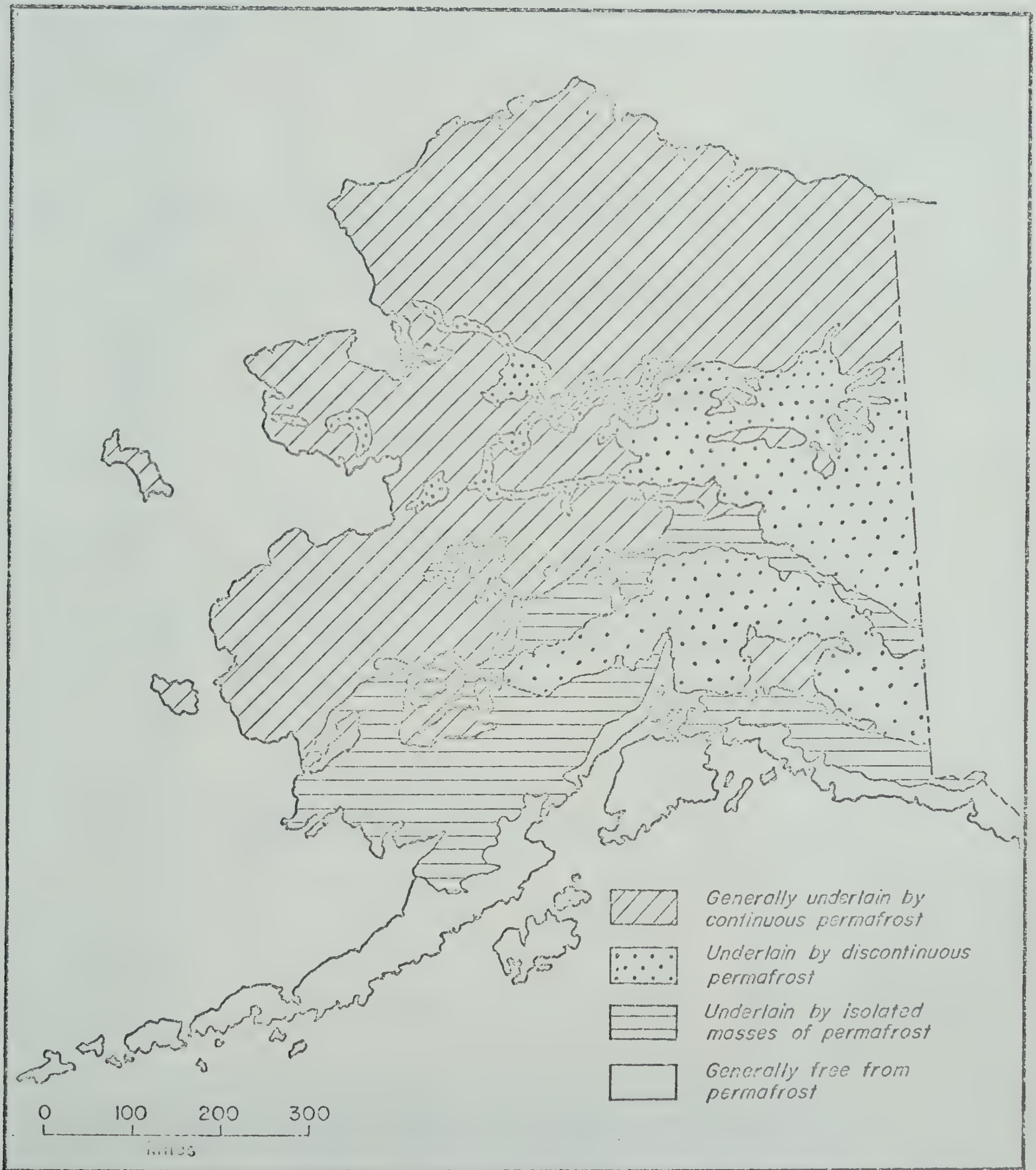

Figure 1 - Permafrost regions of Alaska (From Environmental Atlas of Alaska)

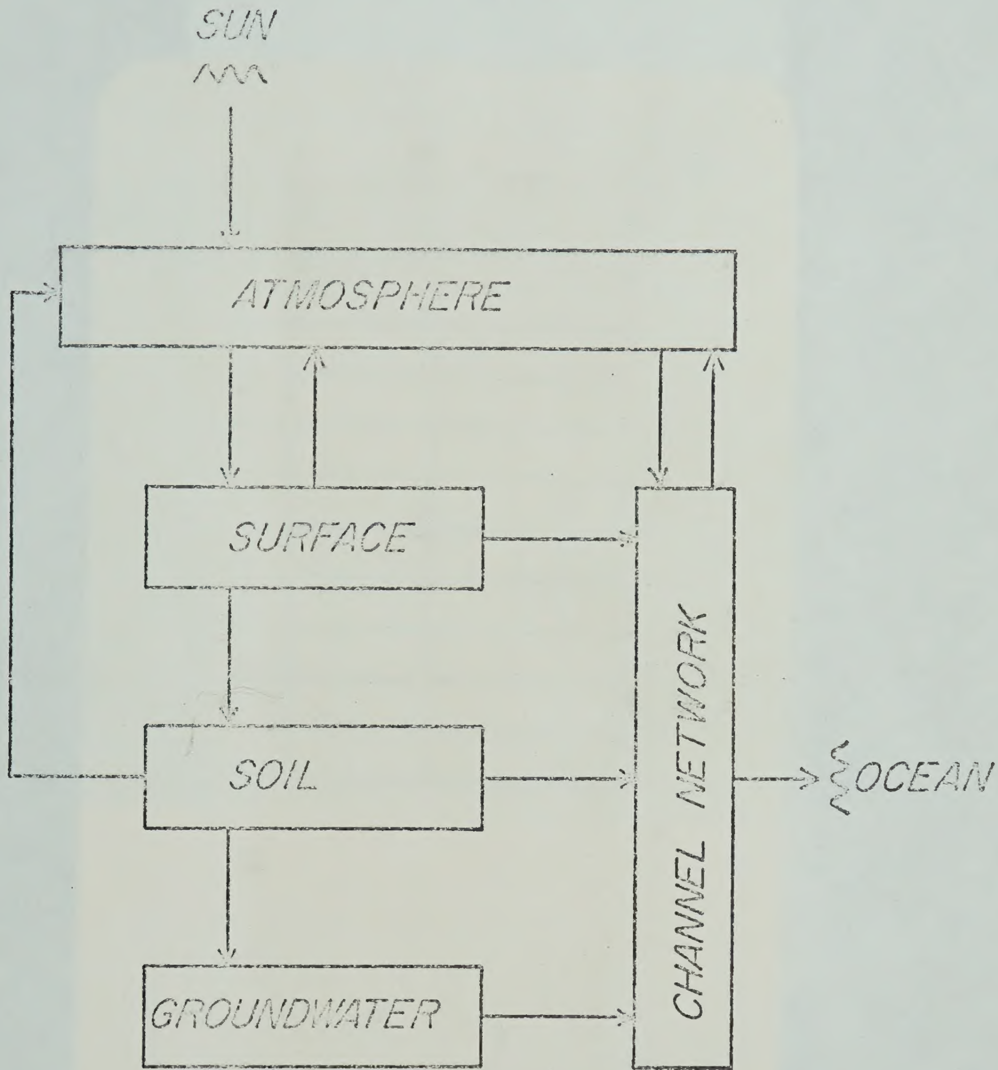

Figure 2 - A representation of the hydrologic system: energy and mass transfer

DATE DUE SLIP

F255